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CORRELATION OF OPERATION SNOWBALL GROUND MOTIONS WITH DYNAMIC PROPERTIES OF TEST SITE SOILS

by

A. J. Hendron, Jr.

October 1965

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U. S. Army Engineer Waterways Experiment Station
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Vicksburg, Mississippi

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Foreword
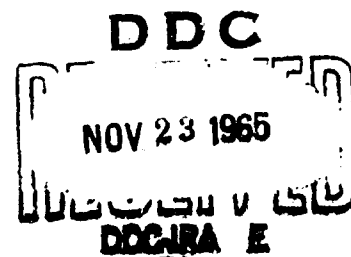
This paper was prepared for presentation at the SNOW BALL Symposium held at Sandia Base, New Mexico, on 19-21 January 1965, under sponsorship of the Defense Atomic Support Agency (DASA).

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Contents

Summary

In this paper the dynamic properties of the soil profile near the
location of the Snowball detonation (Suffield Experimental Station,
Watching Hill Site, Alberta, Canada) are given which pertain to the
prediction of the airblast-induced ground motions in the superseismic
region. Predictions based upon the available dynamic properties are
given and compared with the ground motions measured by the Waterways
Experiment Station.

CORRELATION OF OPERATION SNOWBALL GROUND MOTIONS
WITH DYNAMIC PROPERTIES OF TEST SITE SOILS

Introduction

1. The purposes of this paper are to present the results of dynamic tests which were conducted on undisturbed samples of soil obtained near the location of the Snowball shot, and to show how the soil properties were used to predict peak transient displacements in the superseismic region. A comparison of the computed and observed ground displacements at stations 200 and 250 ft from ground zero (GZ) is given.

Site Conditions

2. The Snowball shot was detonated at a location on the Suffield Experimental Station, Alberta, Canada, known as Watching Hill. Within the immediate area of the explosion the ground surface was essentially level at an elevation of approximately 2167.0 ft (mean sea level). A general description of the geology is given in reference 1. The location of GZ was in the southern end of an area known as the Ross Depression. This depression has apparently once been covered by a large lake, and the soils to a depth of 200 ft are lacustrine deposits consisting of fairly uniform beds of clays and silts with occasional sand lenses. As is usually the case, desiccation and weathering have altered the upper 30 ft. A recent seismic survey[2*] indicates that the upper 23 ft of this deposit has a seismic velocity of approximately 1050 fps, whereas from a depth of 23 ft to 200 ft, references 1 and 2 indicate a seismic velocity of approximately 5100 to 5500 fps. The water table was located at a depth of 23 ft at the time of the test.

3. The bedrock at the site is also described by G. H. S. Jones,[1] but in general the surface of the bedrock at a depth of 200 ft is too deep to influence the ground motion in the superseismic region which, of course, is the subject of this study.

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* Raised numerals refer to items in the Literature Cited.

Soil Profile

Exploratory borings

4. The subsurface conditions of the site were delineated by borings.
The majority of these borings were used for construction of sand columns
and installation of free-field transducers. The locations of borings in
which undisturbed samples were taken for testing by the Waterways Experiment Station (WES) are shown in fig. 1 and are designated borings A, B, C,
D, E, and F. WES also obtained undisturbed samples from the borings
designated R and N17 for the Air Force Weapons Laboratory; the results of
dynamic tests and classification tests conducted on these samples have been
reported by Davisson and Maynard.[3] Only one continuous undisturbed boring
(boring A) was drilled; a relatively few undisturbed samples were obtained
at various depths from the other borings.

Laboratory test results

5. The samples sent to the laboratory were subjected to routine
identification and classification. Unconfined compression strengths were
determined and several consolidation tests were conducted. Vibration tests
and unconsolidated, undrained triaxial tests were conducted and reported
by the firm of Shannon and Wilson.[4] In addition to the tests described
above, a new type of dynamic test was conducted on one of the Suffield
samples in the Small Blast Load Generator (SBLG) at WES; this test will
be described in detail later.

6. Fig. 2 shows typical grain-size distribution curves obtained
from representative samples from various depths. As a result of the various laboratory tests described above, the soil profile has been divided
into representative layers as shown in fig. 3. From the surface to a depth
of approximately 12 ft, the soil is a friable silty clay with a water
content of approximately 9 percent and an unconfined compressive strength,
q_u , ranging from 3.75 to 4.5 tons/ft^2. Atterberg limits determined for
samples from this stratum indicate that the liquid limit, LL , ranges from
38 to 43 and the plastic limit, PL , from 21 to 23; therefore, this soil
would be classified as CL in the Unified Soil Classification System.

7. From a depth of 12 to 27 ft the soil is a brown silty clay with
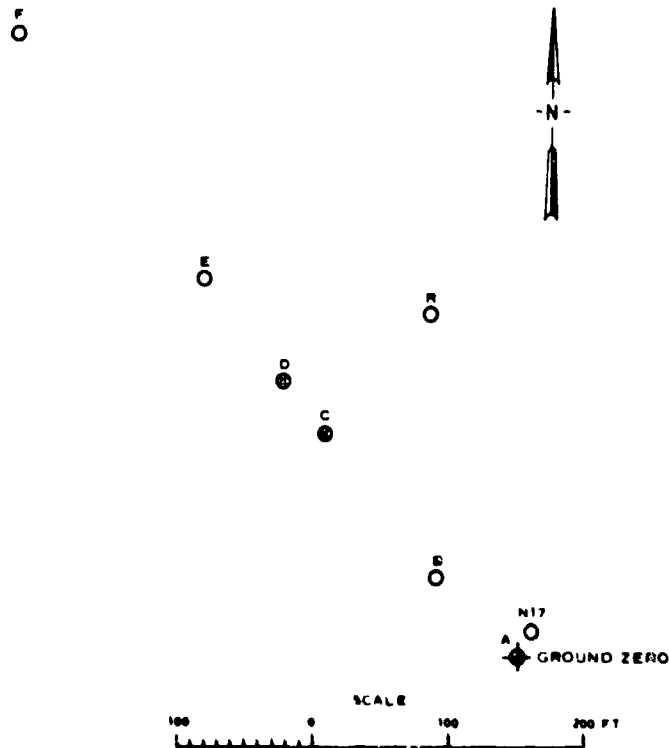a water content of 35 percent and an unconfined compressive strength
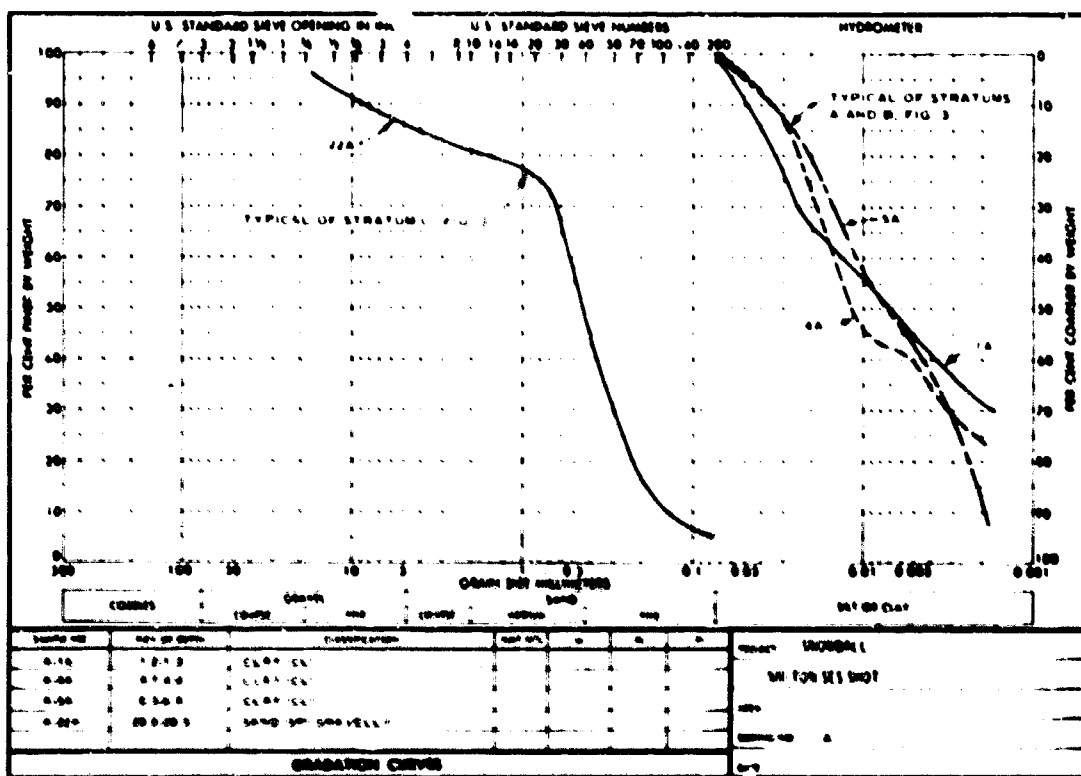
Fig. 1.   Boring plan

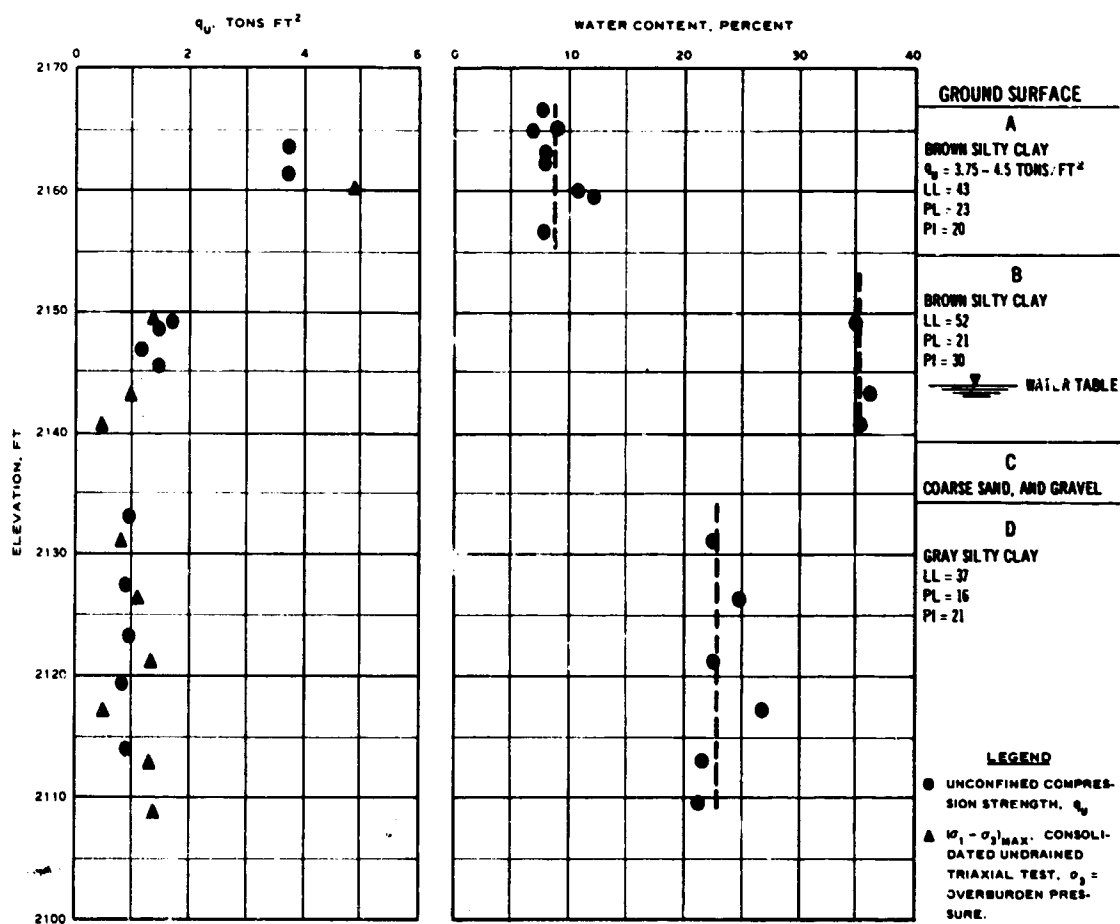Fig. 2.   Typical grain-size distribution of samples from various depths

Fig. 3. Variation of index properties with depth for soil profile at ground zero of Snowball shot

varying from 1.8 tons/ft^2 near the top of the layer down to 1 ton/ft^2 at
the bottom of the layer. The liquid limit of this layer ranges from
48 to 52 percent and the plastic limit is about 21 percent. Therefore,
this soil is somewhat more plastic than the layer immediately above, and
it is borderline between a CL and a CH in the Unified Soil Classification
System. From a depth of 27 to 32 ft, an interbedded stratum of coarse
sand and gravel, which was encountered in boring A, is shown in fig. 3;
this stratum was encountered in all three borings, A, B, and C, but at
different levels. The grain-size distribution of a sand sample from this
layer is shown in fig. 2. From a depth of 32 ft down to at least a depth
of 67 ft the soil is a gray silty clay. The water content in this layer is
about 23 percent, and the unconfined compressive strength averages about
1 ton/ft^2. The liquid limit is 37 and the plastic limit is 16; therefore,
this clay is a CL in the Unified Soil Classification System. Several
consolidation tests were run on samples from this stratum and the analyses
of the e log P curves indicate that the layer is essentially normally
loaded with a compression index of 0.25.

Conditions in the Superseismic Region

8. In the superseismic region the velocity of the air shock, U , as
shown in fig. 4, is much faster than the seismic velocity c in the soil,
such that at relatively shallow depths the angle θ which the front of the
stress wave in the soil makes with the horizontal is relatively small. For
purposes of analysis, the stress wave is assumed to propagate vertically
down the soil column illustrated in fig. 4 such that vertical compression
occurs in the soil with essentially zero, or very limited, lateral strain.
The significant property of the soil under these conditions which controls
the deformation under a given loading is the dynamic constrained modulus
(secant) of deformation M_c . In a constrained or one-dimensional condi-
tion, the general shape of the stress-strain curve is as shown in fig. 5.
At low stresses the stress-strain curve is concave downward, but as the
pressure level increases the curve passes through a point of inflection
and becomes concave upward. The stress level at which the point of inflec-
tion occurs is a function of the natural cementation of the soil, the

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(a)

(c)

STRESS TIME RELATION ON TOP
OF SOIL COLUMN, FIG. 4b

PEAK ATTENUATED
VERTICAL STRESS

θ = ARC SIN C/U

(b)

(d)
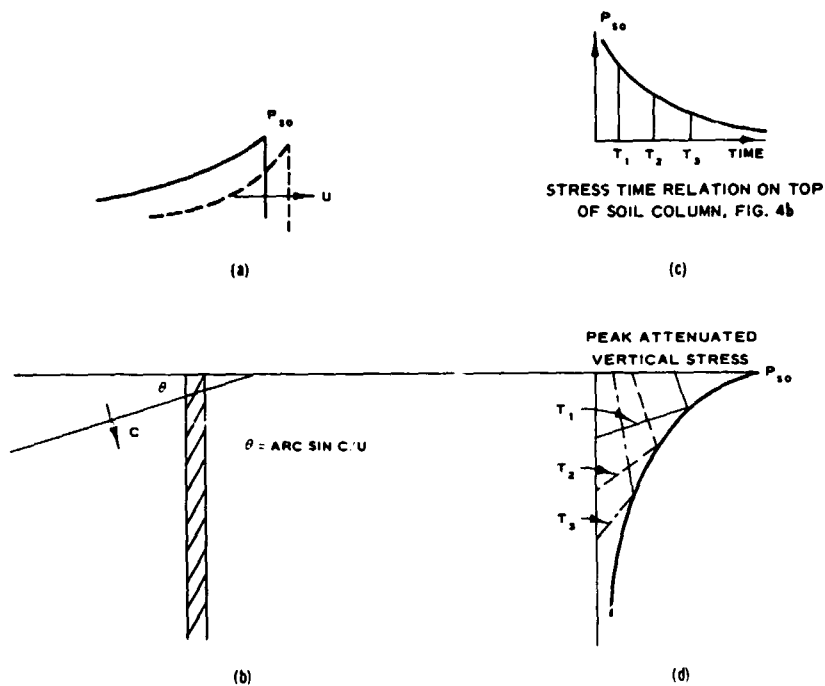
Fig. 4. Typical conditions in the superseismic region

STRESS, σ

$M_{ci} = \rho c^2$ (EQUATION 1)

M_{c1}

σ_2

σ_1

M_{c2}
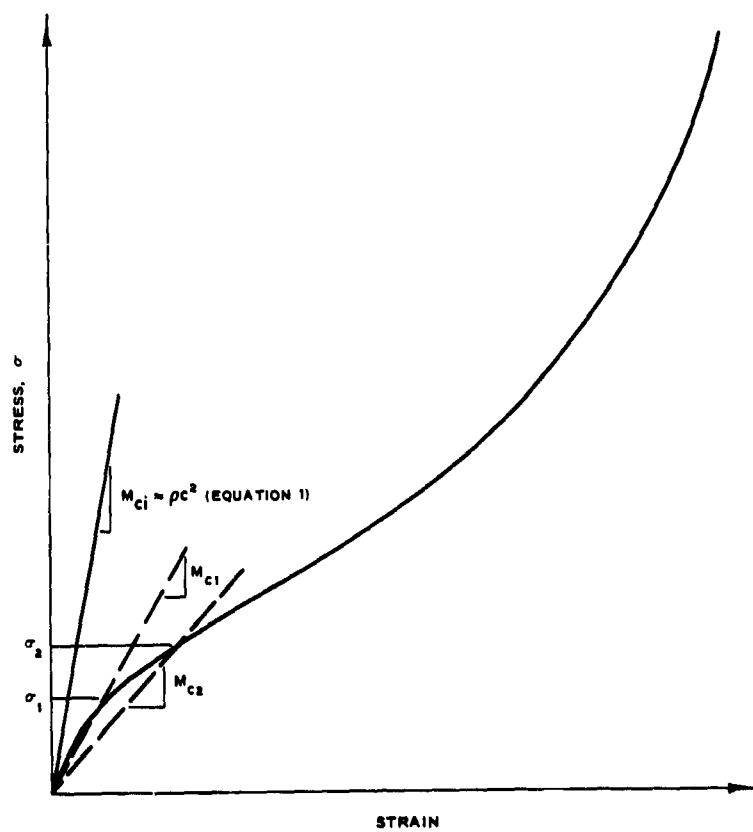
STRAIN

Fig. 5. Typical stress-strain relation for an
undisturbed soil in one-dimensional compression

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maximum preconsolidation load, and the strain rate at which the test was conducted. It has been shown[5] that for nearly identical samples of silt, the point of inflection in a dynamic test occurs at a stress of nearly two times the stress at which the inflection point occurs in a static test. It is quite apparent, then, from fig. 5 that the constrained modulus is very much a function of the pressure level. At low stresses, say less than 1 psi, the constrained modulus is related to the initial tangent M_{ci} shown for the stress-strain curve in fig. 5, and could be estimated from the seismic velocity c in the field by means of equation 1 where ρ is the mass density of the soil.

$$M_{ci} = \rho c^2 \qquad (1)$$

As the pressure level increases, however, the modulus decreases, until some point beyond the point of inflection where the constrained secant modulus begins to increase with pressure. It is imperative, therefore (since the modulus is so dependent upon the stress level), that the procedure used for determining the constrained modulus of undisturbed samples from a given site be conducted at a pressure level commensurate with the pressure level expected in the field at that location. The dynamic testing program on the WES samples was planned so that the stress levels employed would supplement the test results reported by Davisson and Maynard[3] in order that constrained modulus data would then be available on the Suffield Experimental Station soils over a wide range of pressure levels.

Results of Dynamic, Constrained Modulus (Secant) Tests

9. The Wilson vibration apparatus was utilized to test 16 samples of undisturbed soil from the Suffield Experimental Station from depths ranging from 2 to 60 ft. The results of these tests were reported by Shannon and Wilson[4] and are shown in fig. 6. This apparatus essentially gives a modulus of the soil material at very low stress increments; as shown in fig. 6, the modulus as determined by this type of test varies from about 24,000 psi at the surface to 13,000 psi at a depth of 10 ft, and from a depth of 10 to 59 ft is nearly constant between the values of 12,000 and 15,000 psi.
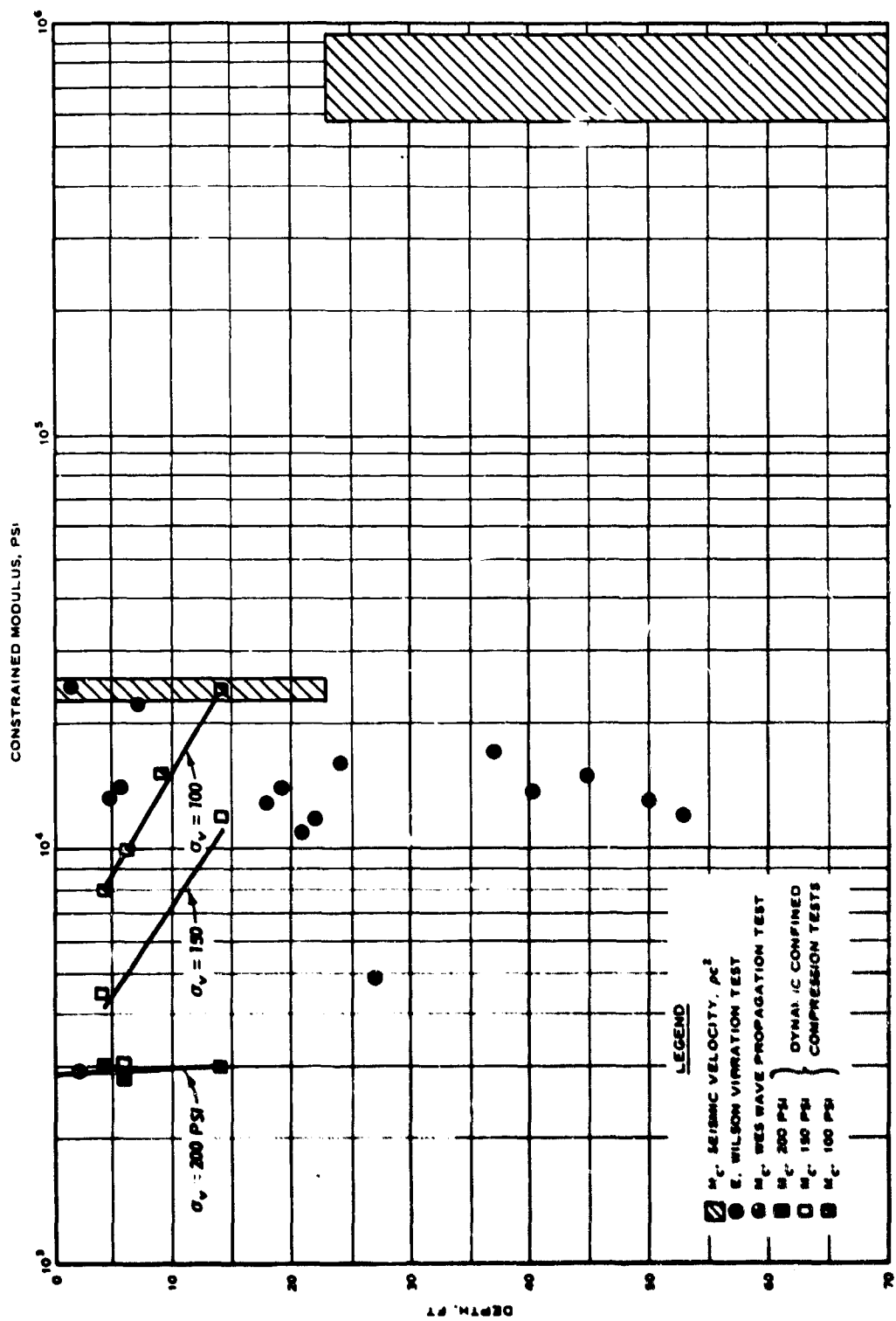
Fig. 6. Dynamic constrained moduli-depth relations

10. The constrained dynamic moduli as back-calculated from the seismic velocities by equation 1 are also shown in fig. 6. From 0 to 23 ft the seismic velocities indicate a constrained modulus of 24,000 psi. From a depth of 23 to 70 ft the seismic velocities indicate a constrained modulus which ranges from 600,000 to 900,000 psi. The discontinuity in seismic velocities at a depth of 23 ft indicates that at the time of the seismic survey the water table was at a depth of 23 ft. It should be noted that the constrained moduli as back-calculated from the seismic values are somewhat higher than the constrained moduli as given by the Wilson vibration tests because the stress levels involved in the seismic pulse are even lower than the stress levels utilized in the Wilson vibration tests.

11. Dynamic, confined compression tests were also conducted at the University of Illinois for the Air Force Weapons Laboratory.[3] The results of these tests are also shown in fig. 6. The dynamic, confined compression tests were conducted with an apparatus as shown in fig. 7; in these tests the sample is confined by a steel ring and loaded dynamically with a gas loader which subjects the sample to stress levels commensurate with those expected in the field. The dynamic constrained moduli as determined from these tests are shown in fig. 6 for the 200-, 150-, and 100-psi stress levels. At an overstress of from 200 to 300 psi, the modulus as determined from the dynamic, confined compression tests is about 3000 psi for a depth of 0 to 15 ft. The constrained dynamic modulus at 150-psi overpressure increases with depth, as shown in fig. 6, from a value of 4500 psi at a depth of 5 ft to a value of 12,000 psi at 15 ft. At an overpressure of 100 psi, the constrained modulus also increases with depth from a value of 8000 psi at a depth of 5 ft, 10,000 psi at a depth of 6 ft, 15,000 psi at a depth of 9 ft, to 24,000 psi at a depth of 15 ft. These data indicate clearly that as the stress level increases at a given depth the constrained modulus decreases; and that for any given value of the vertical stress, σ_v , the constrained modulus generally increases with depth.

12. The constrained modulus as calculated from the propagation velocity of the peak stress in a wave propagation test conducted at the WES* is

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* Feasibility of Small Blast Load Generator Wave Propagation Velocity Measurements on Undisturbed Soil Samples, memorandum for Chief, Nuclear Weapons Effects Division, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, March 1965.
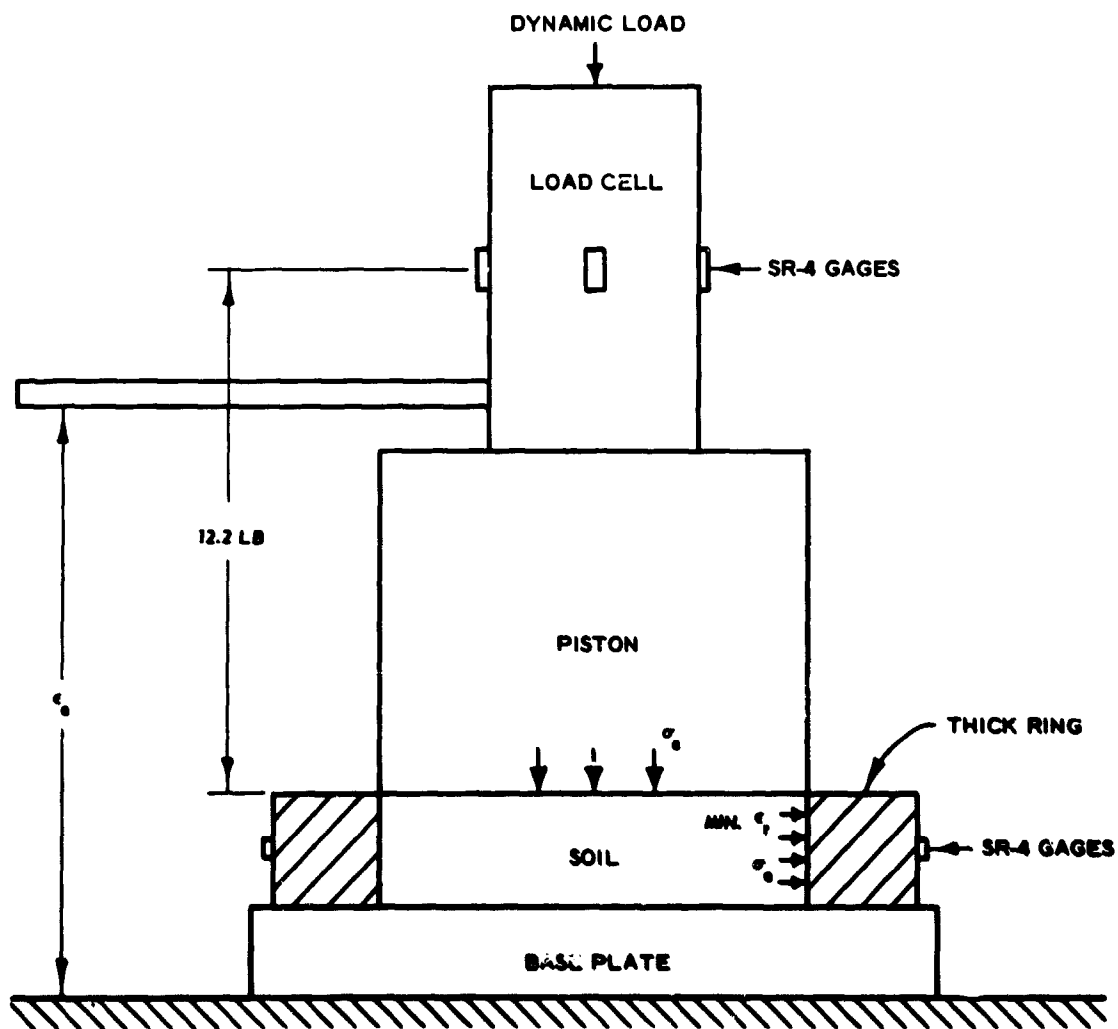
Fig. 7. One-dimensional test

also shown in fig. 6. This test was conducted on a sample from a depth of 2 ft at a stress level of 250 psi; the results indicated an effective modulus of 2900 psi which is in good agreement with the constrained modulus values at this stress level as determined from the dynamic, confined compression tests described by Davisson and Maynard.[3] The general objective of this test was to measure the peak stress wave velocity and residual strain in an SBLG test on a 5-in.-diameter undisturbed sample utilizing a dynamic pressure pulse of the same magnitude as encountered in the field. The undisturbed sample was placed in a semicircular cradle, and the cardboard and wax protection were partially trimmed away, as shown in fig. 8a, to form a "stacked ring device" around the sample in order to minimize friction losses during the dynamic loading in the SBLG. At locations shown in fig. 8b, Illinois Institute of Technology Research Institute (IITRI), miniature stress gages were inserted into cavitites carved in the center of the sample as shown. The sample was then placed in the SBLG and surrounded with two sheets of teflon, which were in turn surrounded by dense sand. During placement of the sample in the generator, IITRI pressure cells were placed at the top and bottom of the sample and a Road Research Laboratory (RRL) cell was placed in the sand at a level corresponding to the base of the sample. The bonnet of the SBLG was then secured over the specimen, and the generator was fired at a pressure of 250 psi. The test results indicate that the average velocity of the peak stress in the top 0.86 ft of the Snowball specimen was 370 fps. (The peak stress velocity in the sand was 1080 fps.) The peak stress wave velocity was measured in the Snowball experiment[6] from times of arrival on pressure gages arranged in a vertical column near the 300-psi range (boring C). The field measurements indicated that the peak stress velocity was 390 fps in the upper 13 ft. Thus, the WES wave propagation test on an undisturbed sample yielded a peak stress wave velocity for the Suffield soil which was in good agreement with field observations. Also the effective modulus back-calculated from the velocity of the peak stress is in good agreement with the constrained modulus determined at comparable pressure levels in the dynamic, confined compression tests reported by Davisson and Maynard.[3] It is therefore concluded that the type of wave propagation test conducted at WES looks quite promising and should be investigated further.
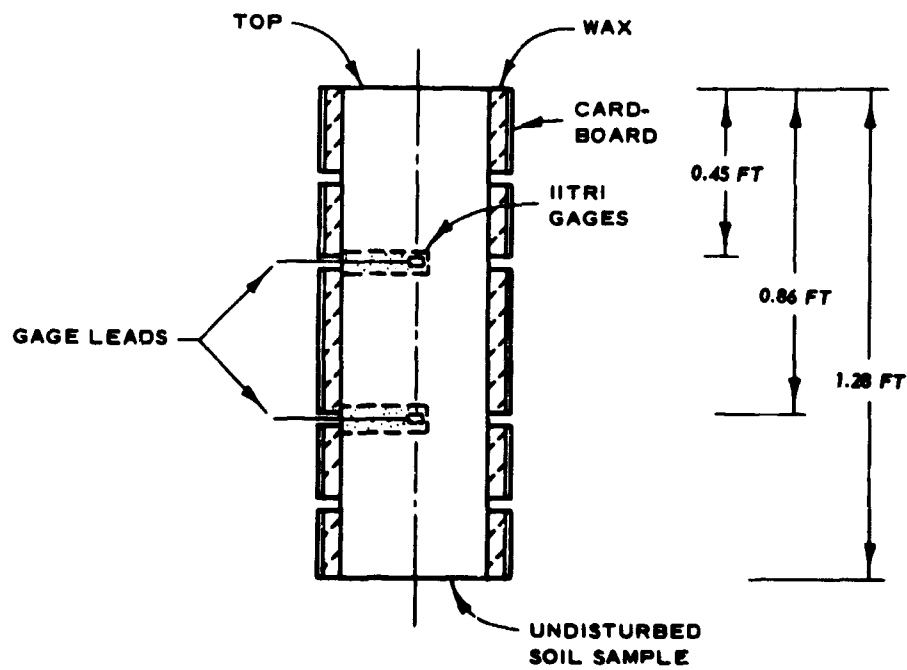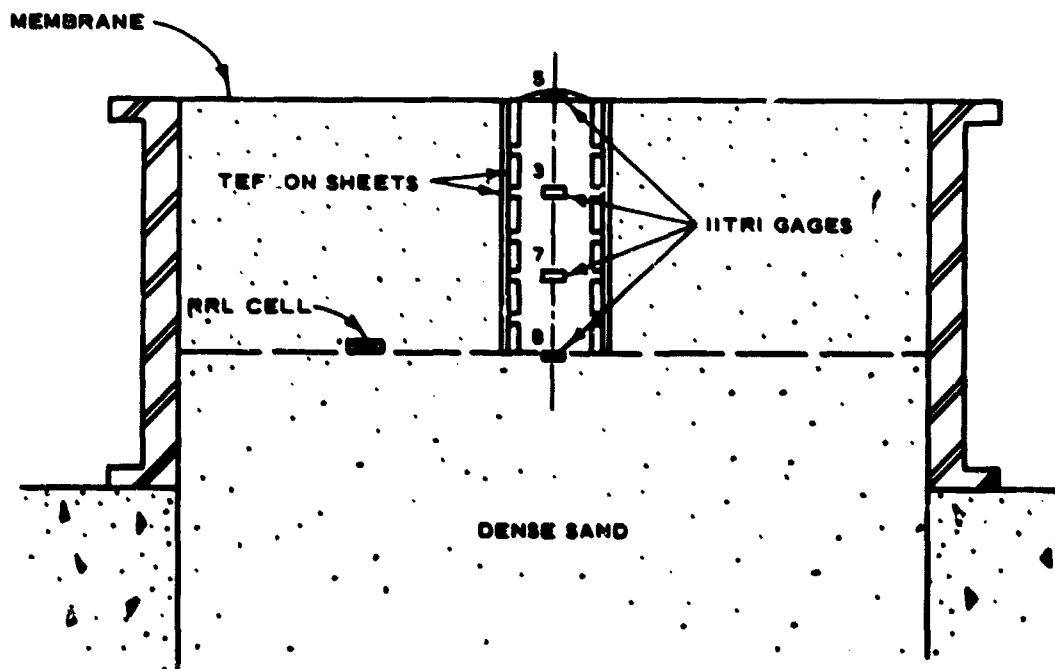
Fig. 8. Small Blast Load Generator wave propagation test setup

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13. The aforementioned test results and discussions demonstrate the dependence of the effective constrained modulus on the pressure level. Both the field observations and laboratory tests conducted at higher over-pressures demonstrate the stress wave velocity for a peak stress between 200 and 300 psi to be about 4/10 of the seismic wave velocity for the top 13 ft of this soil profile. These data then only serve to demonstrate that the seismic velocity is at best only an index property of the profile which serves to give an upper limit to the velocity of propagation and an upper limit to an effective constrained modulus.

14. These data indicate that constrained moduli values back-calculated from the seismic velocity could be in error by as much as a factor of 8 for those shallow portions of the soil profile subjected to an overpressure of 200 to 300 psi. An example follows which demonstrates the use of a procedure for selecting the constrained modulus with depth at a given location if the peak side-on overpressure at the surface can be estimated prior to the shot.

Selection of a Constrained Modulus-Depth Relation

15. Since the effective constrained modulus at a given depth is a function of the peak vertical stress at that depth, the first step in the selection of a constrained modulus-depth relation is to estimate the attenuation of vertical stress with depth. Predicting the attenuated peak vertical stress with depth has been the object of considerable study and will not be discussed in detail here; the method used will be essentially that given in the Air Force Design Manual.[7] It is well established that this method gives results which are in fairly close agreement to pressures observed in the field even though a recent study[8] has shown the assumptions underlying this method to be questionable.

16. In this method, the peak vertical stress σ_v at depth z can be expressed as a function of the peak side-on overpressure P_{so} and the attenuation factor as given in equation 2

$$\sigma_v = \alpha_z P_{so} \tag{2}$$

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Where, α_z is given by equation 3

$$\alpha_z = \frac{1}{1 + z/L_w} \qquad (3)$$

and L_w is given by equation 4

$$L_w = 230 \text{ ft} \left(\frac{100 \text{ psi}}{P_{so}}\right)^{1/2} \left(\frac{W}{1 \text{ MT}}\right)^{1/3} \qquad (4)$$

17. A curve of the calculated peak attenuated vertical stress with depth is shown in fig. 9b for a location 200 ft from GZ, which corresponds to WES boring C. At this range the predicted value of the peak side-on overpressure by BRL[9] was 310 psi. In fig. 9a are shown the various data which define the variation of the dynamic constrained modulus with depth for the Suffield Experimental Station soils as determined by the test procedures described previously which utilize various levels of stress. The task then is to look at the data available on the soil in fig. 9a and the predicted attenuated vertical stress in fig. 9b and construct a constrained modulus-depth curve which accounts for the pressure level expected at a given depth. For example, the dynamic test results have shown that samples taken near the surface and subjected to dynamic overpressures in test devices from 200 to 300 psi will have a constrained modulus of about 3000 psi. Therefore, at the 200-ft station, which has a peak overpressure at the surface of 310 psi, elements of soil near the surface will be expected to have a constrained modulus of 3000 psi. At a depth of 10 ft at the 200-ft station, the peak attenuated stress as given by fig. 9b is approximately 150 psi. Therefore, at a depth of 10 ft on fig. 9a the constrained modulus of interest would be 7000 psi, the value of the constrained modulus where the 150-psi line passes through a depth of 10 ft. At deeper depths (15 to 23 ft), the constrained modulus should approach the 14,000- to 15,000-psi value as given by the Shannon and Wilson vibration test, becau it has been shown previously[10] that the Wilson vibration test gives a reliable value of the constrained modulus when the strain recovery approaches 100 percent. Since the degree of saturation in the 15- to 23-ft depth range is over 96 percent, the residual strains for vertical stresses approaching 100 psi, as is the case at this station, are very
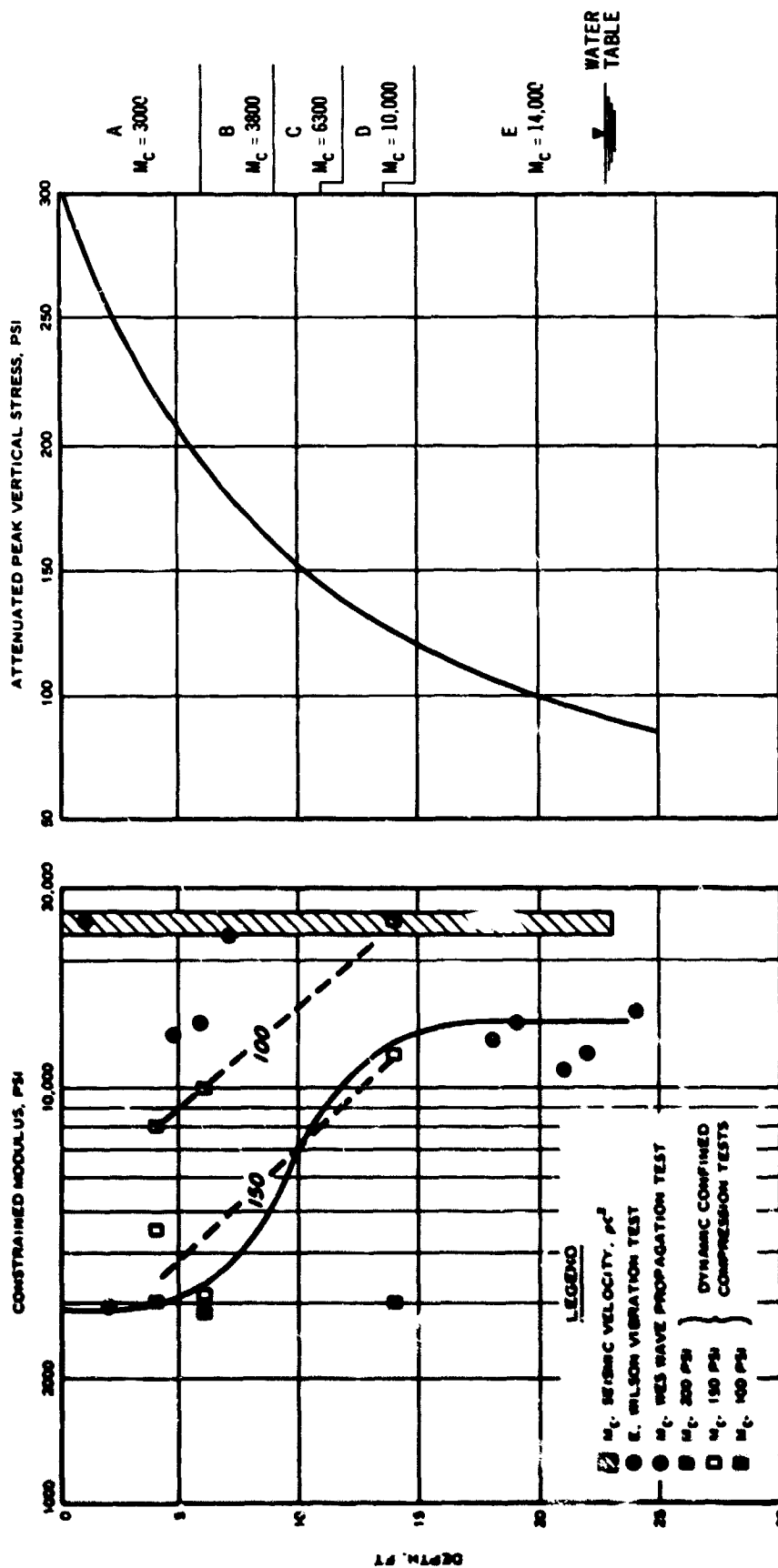
Fig. 9. Constrained moduli-peak attenuated vertical stress-depth relations, WES 200-ft station, Operation Snowball

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small. The constrained modulus-depth relation arrived at by the writer for this particular situation is shown by the smooth black line in fig. 9a. This relation is smooth down to a depth of 23 ft where the water table table would cause an abrupt discontinuity and the constrained modulus would jump to a level of 300,000 psi or more. Since the stress levels in this experiment were very low below a depth of 23 ft, when considered with a constrained modulus of 300,000 or more, the strains below a depth of 23 ft would be insignificant in causing displacements and were not considered in this analysis.

18. The peak, attenuated, vertical stress-depth curve at a range of 250 ft, which corresponds to WES boring D, is shown in fig. 10b. The constrained modulus-depth relation is given by the smooth black curve in fig. 10a and was arrived at by reasoning and judgment similar to that described above.

Airblast-Induced Ground Motion Predictions

19. The peak transient vertical displacements at the surface and a depth of 5 ft have been computed for the 200- and 250-ft stations. The calculations are based upon the predicted peak overpressure at these ranges as given by reference 9 and the overpressure-time curves as shown in fig. 11, which are idealizations of data given by BRL.* The peak vertical stress-depth relation was computed from equations 2, 3, and 4 by the procedure given in the Air Force Design Manual;[7] the attenuated vertical stress-depth relations are shown in figs. 9 and 10.

20. As the airblast arrives at a point on the surface in the superseismic region, an airblast-induced stress wave begins to propagate downward; as it propagates downward the peak vertical stress attenuates and the rise time of the wave increases with depth as shown in fig. 4d (page 6). The rise time increases because the peak stress travels at a velocity lower than the seismic velocity; the seismic velocity is related only to

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* Overpressure Data Obtained by Project 1.1 During Operation Snowball, communication from U. S. Army Ballistic Research Laboratories to Director, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, 17 November 1964.
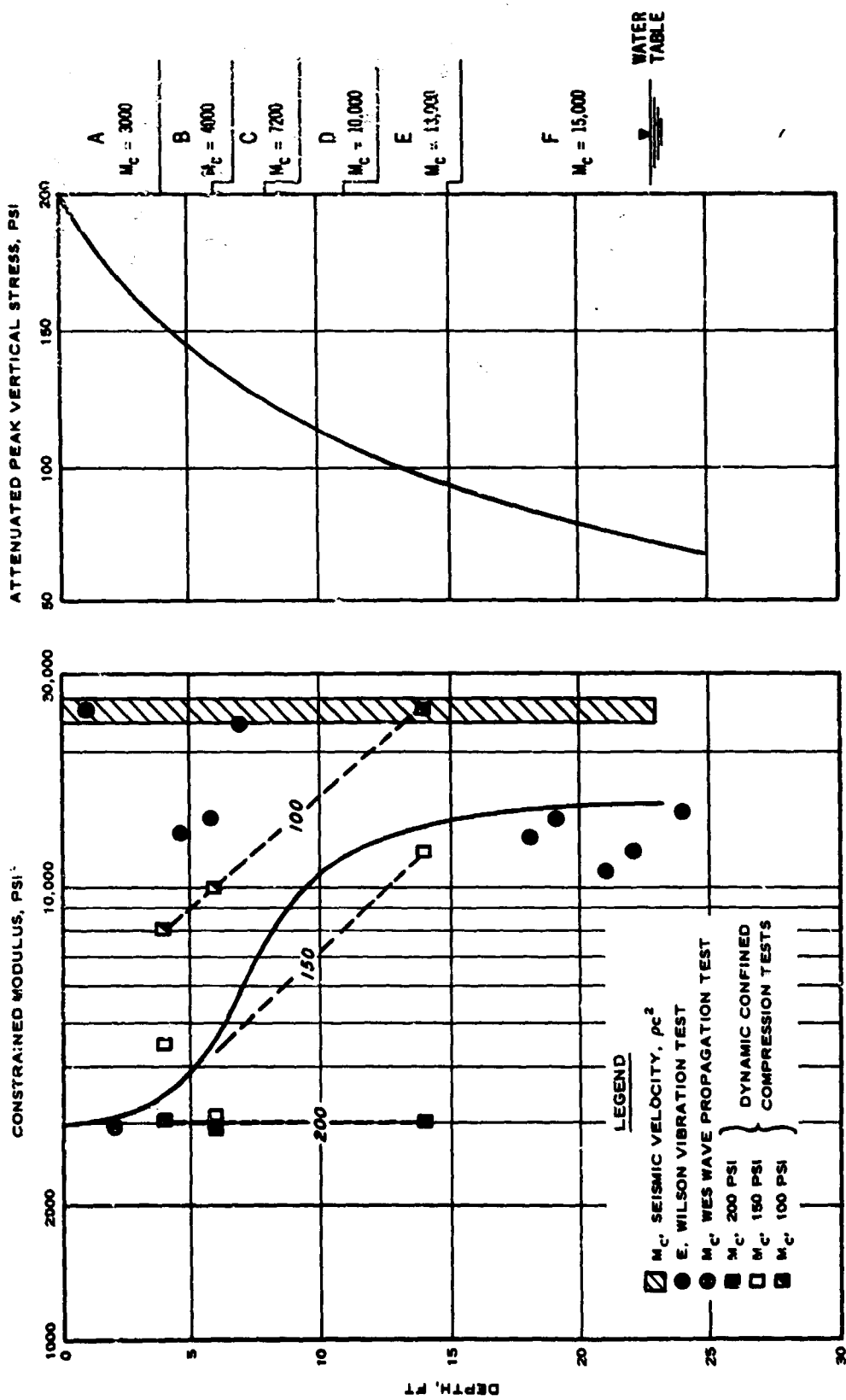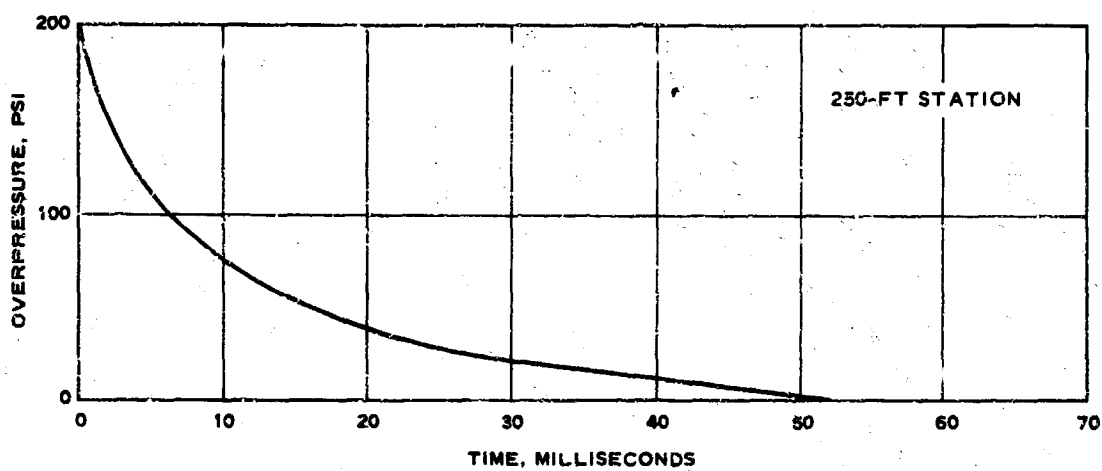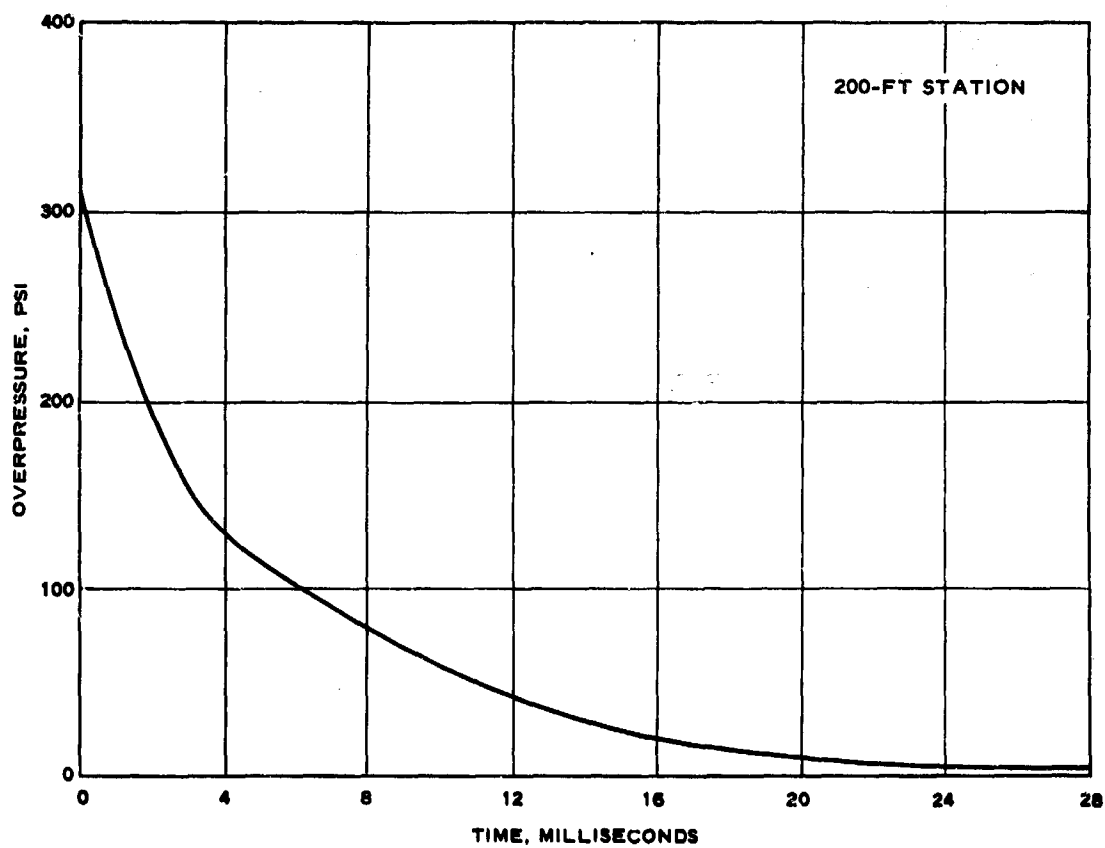
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Fig. 10. Constrained moduli-peak attenuated vertical stress-depth relations, WES 250-ft station, Operation Snowball

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(a)

(b)

Fig. 11.   Idealized overpressure-time relations, Operation Snowball

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the initial arrival of the pulse. For purposes of predicting vertical ground displacements in this study, the position of the stress wave at times T_1, T_2, and T_3, as shown qualitatively in fig. 4d, were determined. At any given time, say T_1, the variation of stress with depth is assumed to be linear between the following critical points: zero stress at the depth of the wave front, the attenuated peak vertical stress σ_v at the depth of the peak stress, and the overpressure at the surface for time T_1 as shown in fig. 4c. At various times the strains within the depth of wave propagation are integrated to give the displacement at the surface. The details of this procedure are outlined in reference 11.

21. For the purpose of predicting ground motion in this study, only the upper 23 ft was considered because the soils above this depth were rather compressible and below a depth of 23 ft, which corresponds to the depth of the water table, the soil had a constrained modulus greater than 300,000 psi; therefore, very small strains would result below this depth for the pressure levels commensurate with the 200- to 250-ft range. The initial pulse was assumed to propagate at a velocity of 1000 fps and the peak stress was assumed to propagate at 500 fps in the upper 23 ft. After the vertical stress-depth relations were determined at various times, as shown qualitatively in fig. 4d, the constrained modulus-depth relations from figs. 9 and 10 were used with the vertical stress-depth relations to arrive at a strain distribution with depth at various times. The strains were then integrated to give the displacements of convenient layers, as indicated by layers A, B, C, D, etc., on the right side of figs. 9 and 10. By summing the displacements of the layers below the surface and below a depth of 5 ft, the displacements at the surface and at a depth of 5 ft were determined. The results of these preliminary calculations yield upper bound, peak, transient surface displacements at the 200- and 250-ft stations of 8.0 ± 0.5 in. and 5.4 ± 0.5 in., respectively, while the calculated peak, transient displacements at a depth of 5 ft at the same two stations are 4.5 and 2.2 in., respectively. Ground-motion measurements by Murrell[12] indicate that the peak, transient displacements at a depth of 5 ft were 4.9 and 2.1 in. for the 200- and 250-ft stations, respectively, which are in reasonable agreement with the ca.   .ted values.

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Conclusions

22. The dynamic constrained moduli data available on the Suffield Experimental Station soils definitely indicate that it is of prime importance to measure the constrained modulus of a soil at the stress levels expected at the location of interest in the field. Direct inference of the constrained modulus from the seismic velocity or vibration tests will greatly overestimate the constrained modulus and result in an underestimation of the ground motion.

23. The wave propagation test conducted at WES on an undisturbed sample of Suffield soil gave the same velocity of the peak stress as observed at the same depth in the field; the constrained modulus back-calculated from this peak stress velocity agrees quite well with the dynamic constrained modulus determined at the same stress level in dynamic, confined compression tests on the same soil at the University of Illinois.[3]

24. The ground displacements predicted on the basis of the dynamic properties of the soil presented herein agree reasonably well with the observed values. It is emphasized, however, that the analysis presented is preliminary and further analysis of the observed ground motions in terms of the dynamic soil properties is needed. Additional analyses of the ground-motion data will be made in the final report on the earth motion study (in publication).

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13. ABSTRACT

In this paper the dynamic properties of the soil profile near the
location of the Snowball detonation (Suffield Experimental Station,
Watching Hill Site, Alberta, Canada) are given which pertain to the
prediction of the airblast-induced ground motions in the super-
seismic region. Predictions based upon the available dynamic prop-
erties are given and compared with the ground motions measured by the
Waterways Experiment Station.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Ground motions, Operation Snowball						
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